Model dependence of cloud radiative kernels: can we use one cloud kernel for all models?

Xianglei Huang[1], Xiuhong Chen[1], Qing Yue[2], Greg Elsaesser[3], Kentaro Suzuki[4], Xianwen Jing[1]

[1] The University of Michigan

[2] JPL/Caltech

[3] NASA GISS

[4]Tokyo University

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Radiative feedback & radiative kernels

Averages of net TOA **broadband** flux

$$\lambda_x = -\frac{\delta \overline{R}}{\delta X}\frac{\delta X}{\delta T_s}$$

$Wm^{-2}\,K^{-1}$

Ts: global-mean surface temperature

X : [Temp, WV, cloud, albedo]

(Soden et al., 2008)

Spectral radiative feedbacks (Huang et al., 2014)

$$\lambda_{x_v} = -\frac{\delta \overline{R_v}}{\delta X}\frac{\delta X}{\delta T_s}$$

$Wm^{-2}\,cm^{-1}\,K^{-1}$

Using monthly-mean CMIP output to compute radiative feedbacks

$$\frac{\delta \overline{R_v}(\mathrm{lat,lon;\Delta t})}{\delta x}\frac{\delta \overline{x}}{\delta T_s}, \qquad \delta \overline{x} = [x]_{2\mathrm{CO}_2} - [x]_{\mathrm{ctl}}$$

Soden et al. 2008
Shell et al., 2008

Radiative feedback & radiative kernels

How to get the radiative kernels $\dfrac{\delta \overline{R_v}(\mathrm{lat},\mathrm{lon};\Delta \mathrm{t})}{\delta x}$

For each (lat, lon)

1. archive 3-hourly output of (T, q, cloud, Ts, ...)
2. compute Jacobian for every 3-hourly time step

$$J_t\left[T(p_i)\right] = \frac{\partial R\left[T(p), q(p), cloud, Ts, \ldots\right]}{\partial T(p_i)}$$

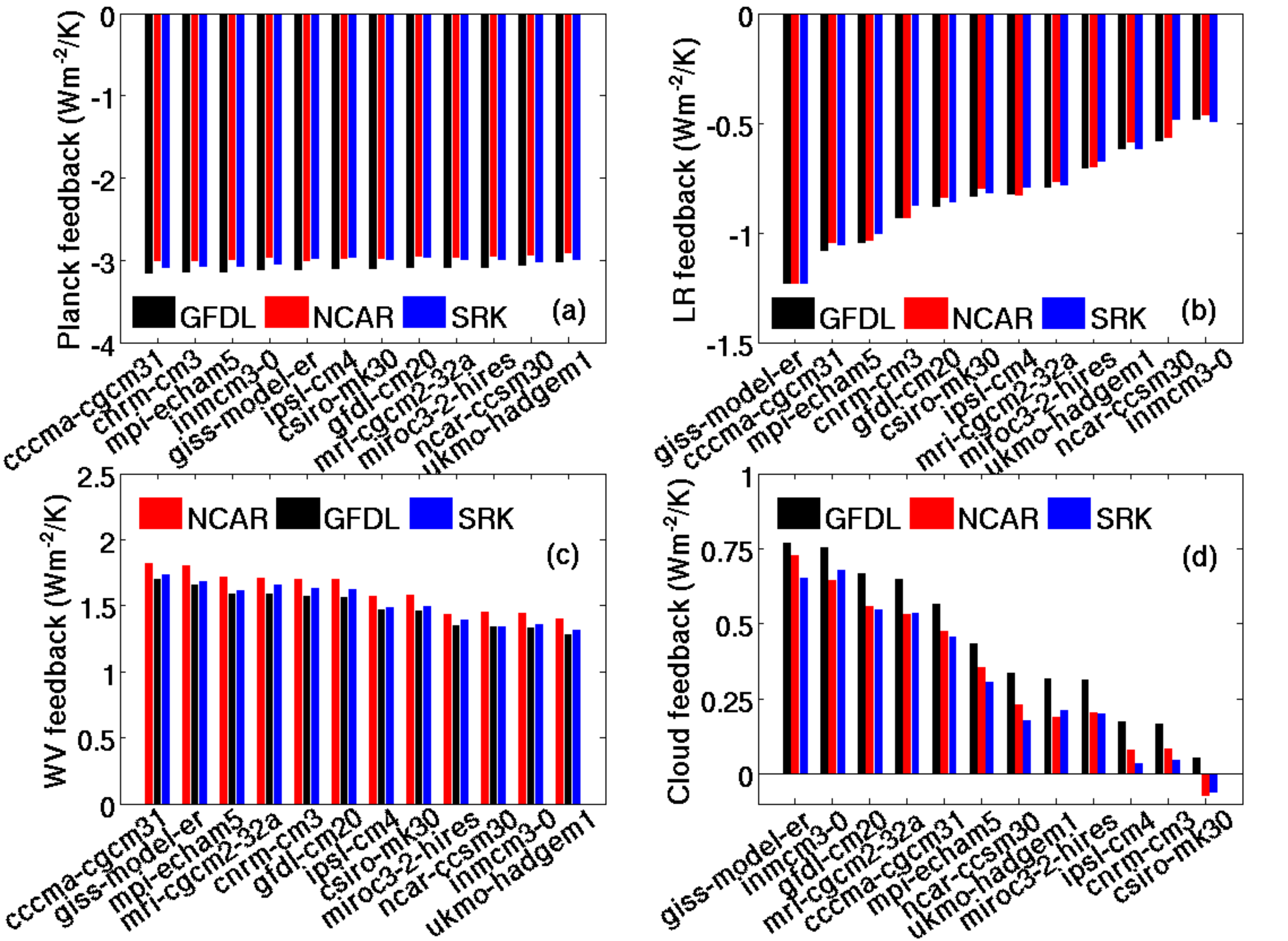
3. average onto each calendar month over many years

$$\frac{\delta \overline{R}(lat, lon; \Delta t)}{\delta T(p_i)} = \frac{1}{N}\sum_{t=1}^{N} J_t\left[T(p_i)\right]$$

Two issues $\frac{\delta \overline{R_v}(\mathrm{lat,lon;\Delta t})}{\delta x}$

- Which data set to use for computing the Jacobian? Will the radiative kernels be model dependent, or one kernel fits all?
- Above procedures work for continuous variables, such as T(p), q(p), Ts, but not for clouds ("non-continuous" var)
  - How to get cloud radiative feedbacks?

Except for clouds, it doesn't matter much which data/RTM used to build the radiative kernels



(Huang et al., 2014)

For the second issue:
adjust method vs. kernel method

- Adjust method (Soden et al., 2008): taking all-sky and clear-sky difference into account (dCRE: diff in cloud radiative effect)

$$\lambda_{cld} = \Big[dCRE + \underbrace{(K_T^0 - K_T)dT + (K_q^0 - K_q)dq + (G^0 - G)}_{\text{adjustment}}\Big]/dT_s$$

- Kernel approach
  - Cloud(lat, lon, pressure) is not suitable for kernel construction. But,
  - Cloud(lat, lon; τ, CTP) is suitable: continuous w.r.t. to (τ, CTP): Jacobican can be well defined
- Huang et al. (2019; GRL) compared spectral details of two methods: adjust method

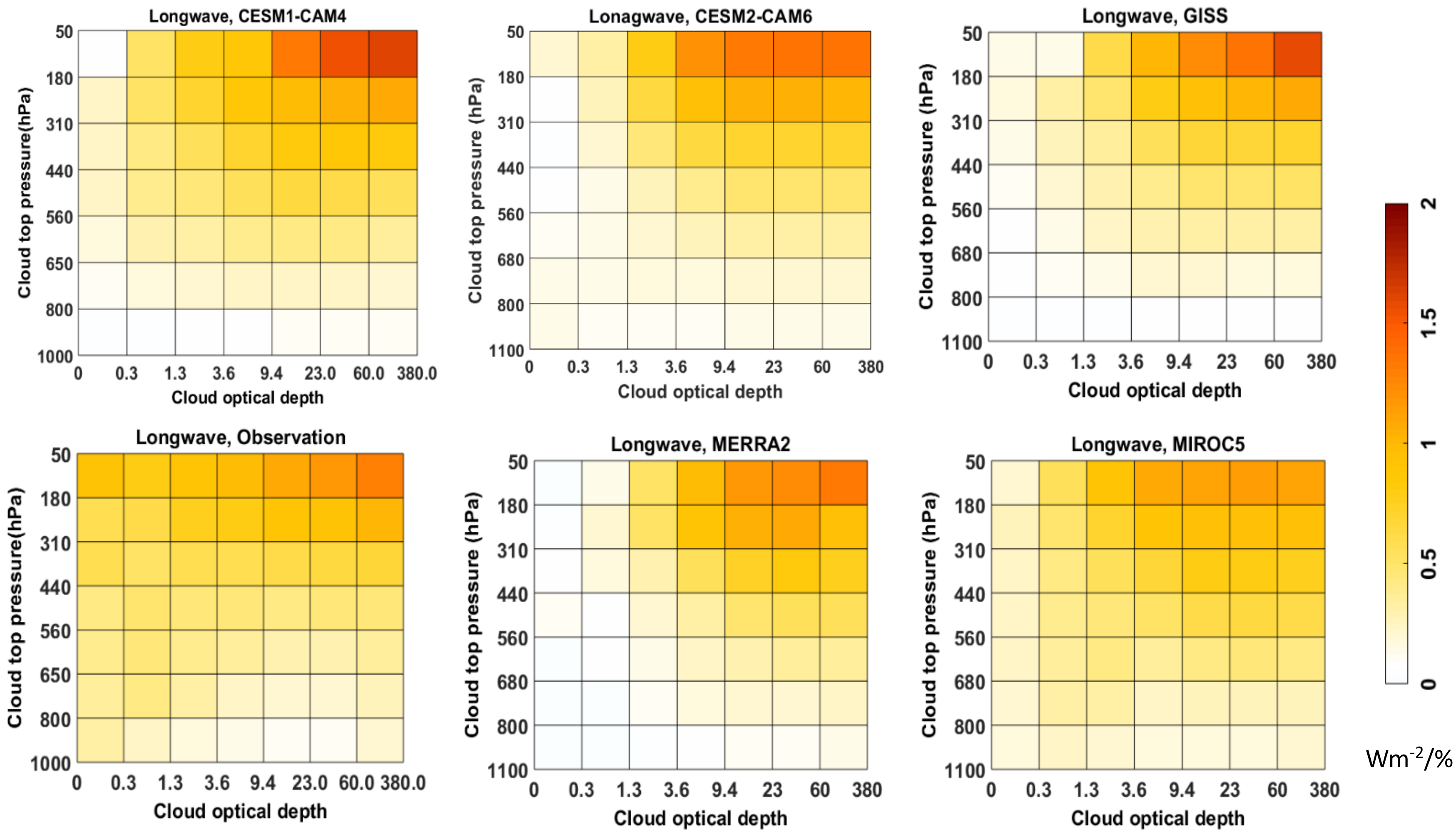
- Zelinka et al. pioneered the cloud radiative kernels in (τ, CTP) space
  - Can be well connected to ISCCP simulator in the models
  - Use Fu-Liou offline radiative transfer model to get Jacobian w.r.t. cloud fraction
  - τ defined at 0.55 um, use formula in F-L code to get $\tau(\nu)$
- Yue et al. (2016) and Huang et al. (2019) took a different approach
  - Accumulate CloudAmount(τ, CTP), TOA flux statistics for each (lat, lon)
  - Regression TOA flux w.r.t. Cloud Amount to get the Jacobian. No off-line RTM
  - Can be done for both observations and models

But still, can we just use one set of cloud radiative kernels for all GCMs?

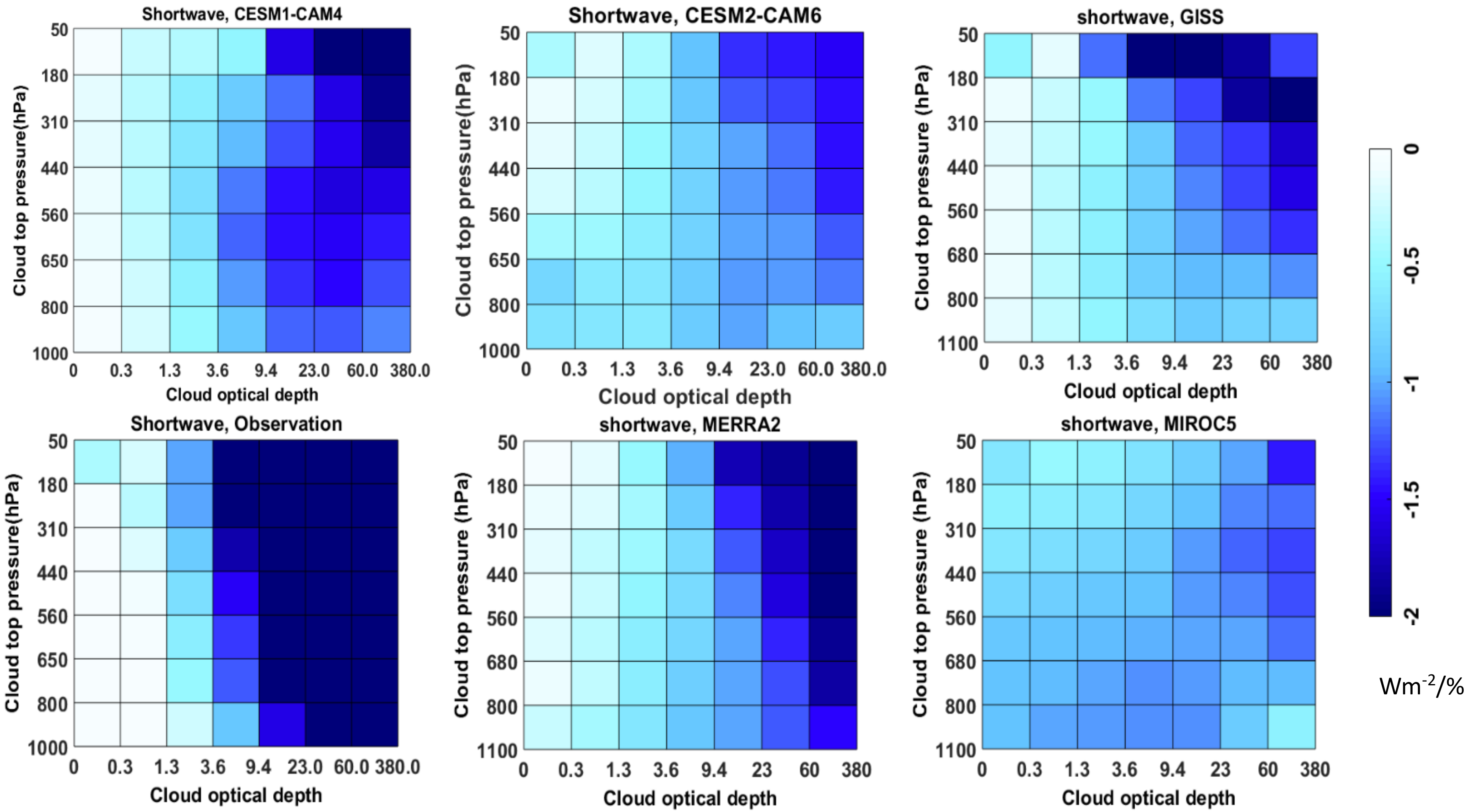
- If one kernel can be used to get CRF from all models, which means
  - The cloud kernels from different models must be similar
  - When cloud kernels from different models are applied to the cloud amount change from a given GCM, it should get similar CRF (a hypothesis to test out!)

Test out the hypothesis with models, obs, and reanalysis

	Temporal resolution	Spatial Resolution (lat by lon)
CESM1 CAM4	3-hourly	1.9° by 2.5°
CESM1 CAM5	3-houly	1.9° by 2.5°
CESM2 CAM6	3-hourly	0.94° by 1.25°
GISS	6-hourly	2° by 2.5°
MIROC5	3-hourly	1.4° by 1.4062°
MERRA-2	3-hourly	1.5° by 1.875°
Observation (Yue et al., 2016)	Footprint level	2.5° by 2.5°

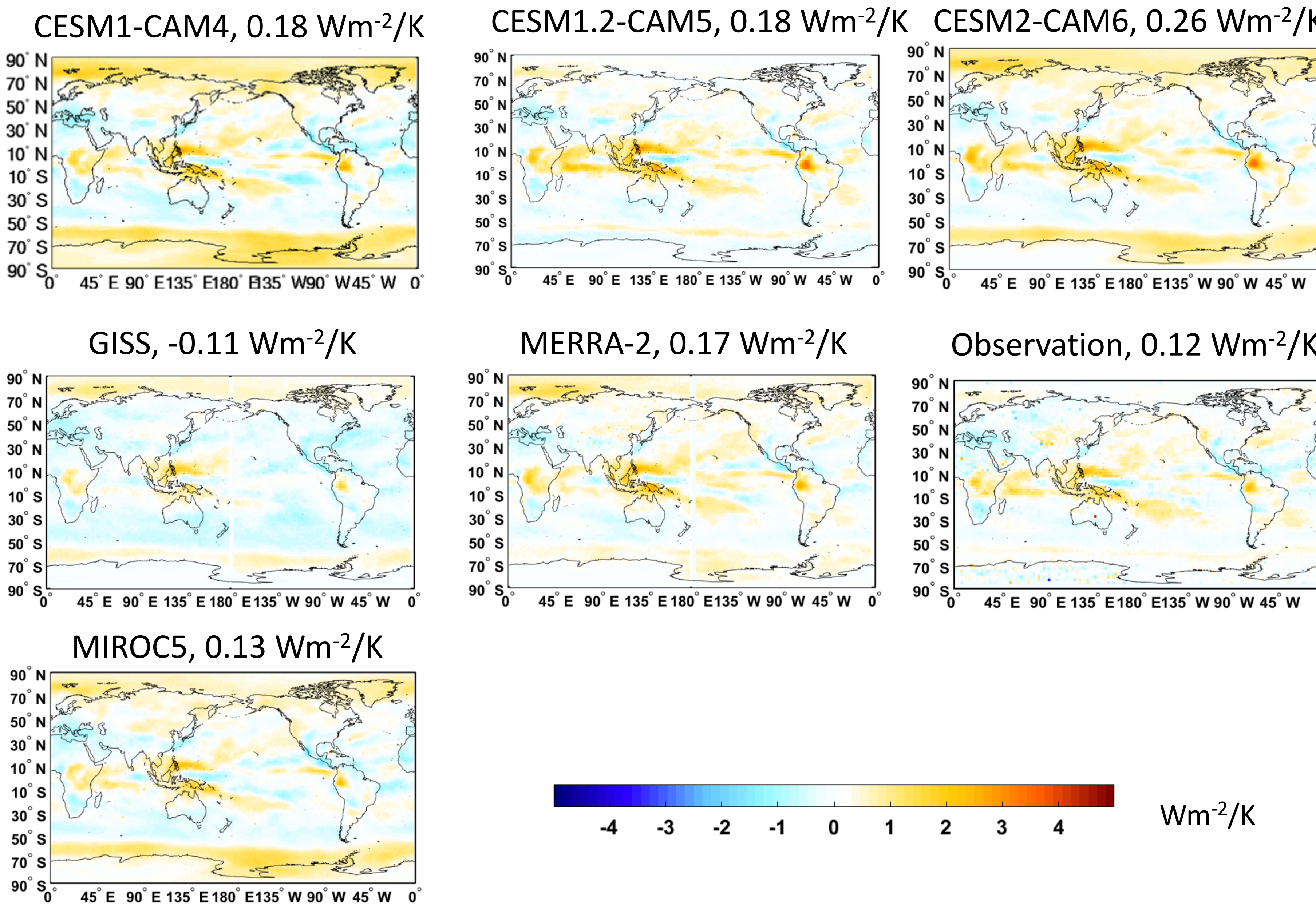


Longwave CRK: January Global average

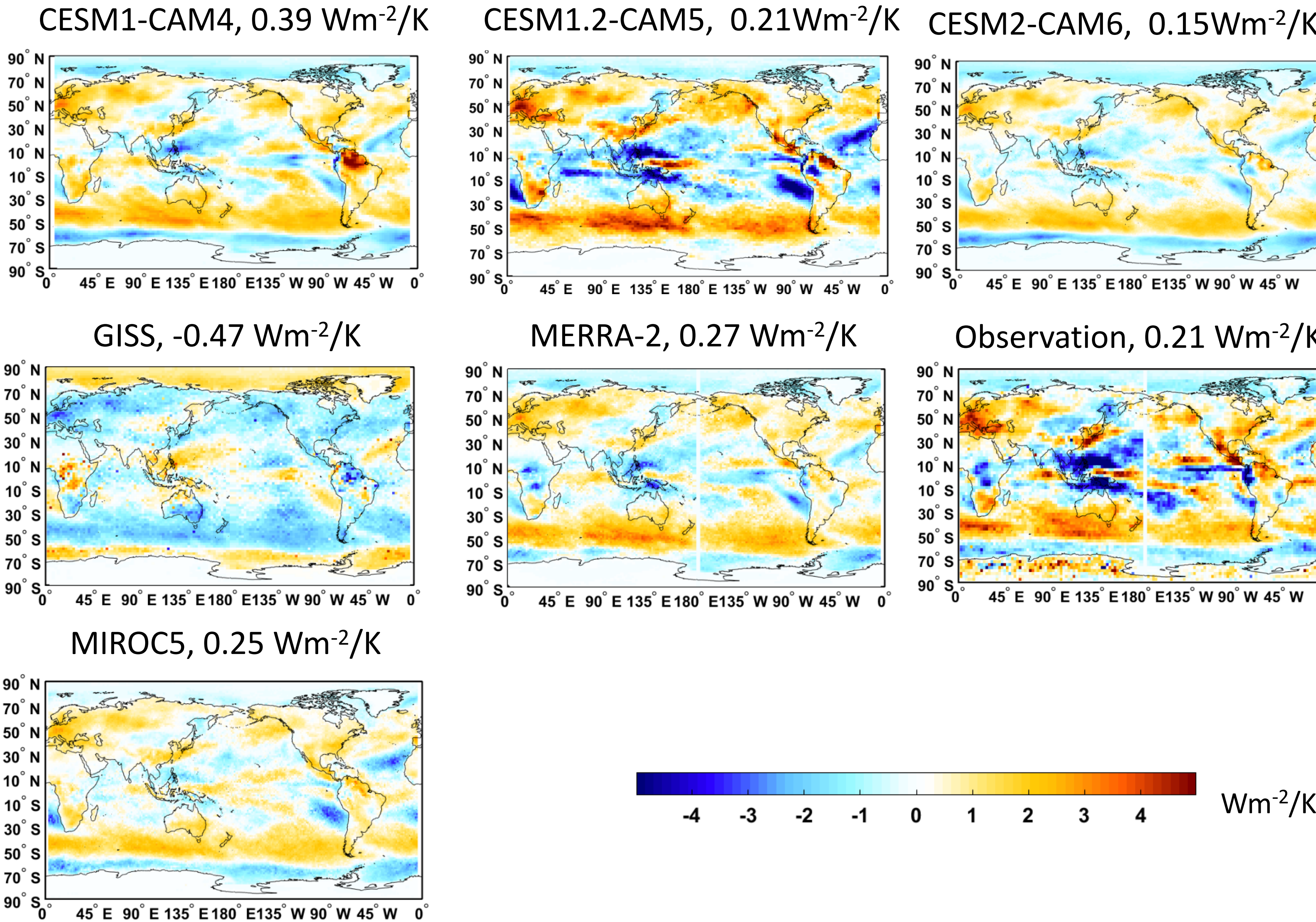


Shortwave CRK: January Global average

LW cloud feedback derived **using different cloud radiative kernels** but the same cloud response from CESM1-CAM4 slab 2xCO_2



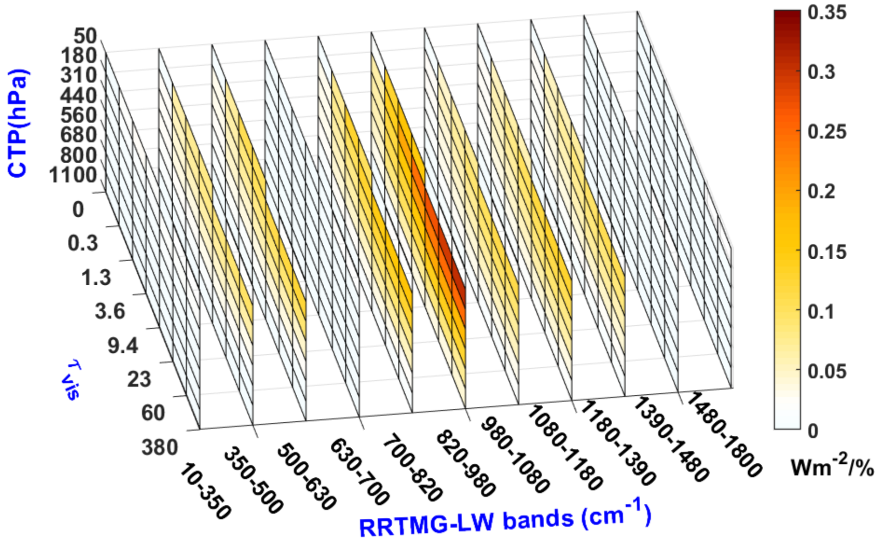
SW cloud feedback computed using different cloud radiative kernels but same cloud response from slab $2xCO_2$



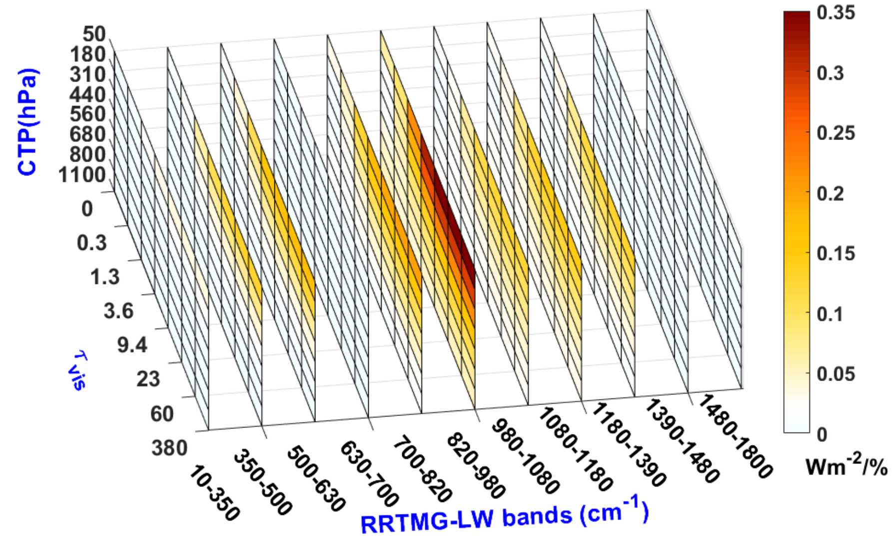
Excursus: spectral decomposition of CRF

We can build CRK for each band out in GCM radiation scheme

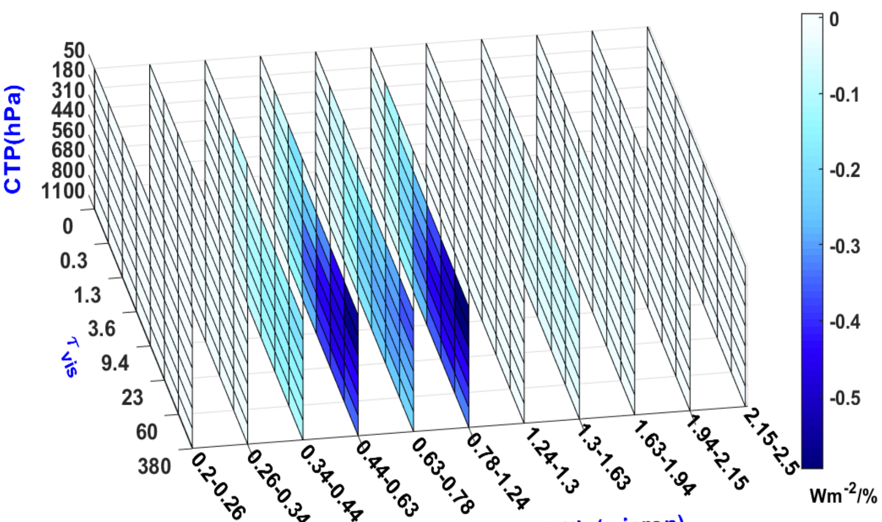
LW, CESM1-CAM4 (global-mean, January)



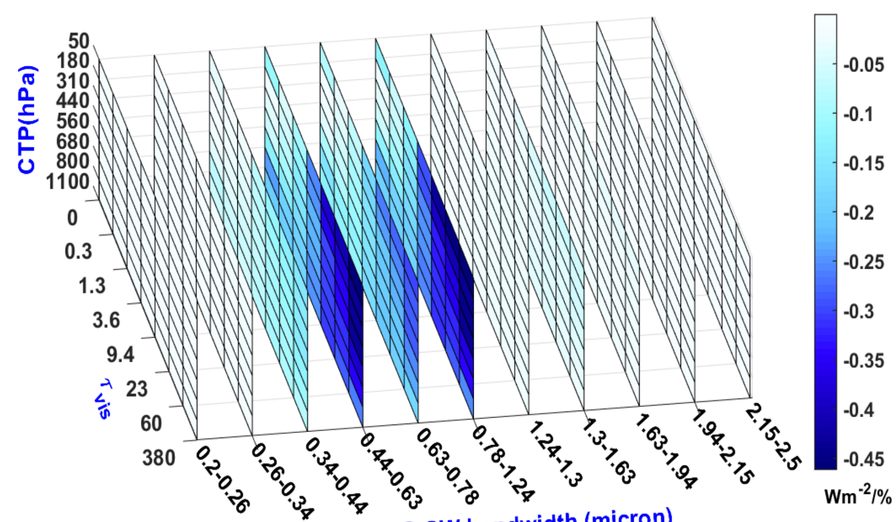
LW, CESM2-CAM6 (global-mean, January)



SW, CESM1-CAM4 (global-mean, January)

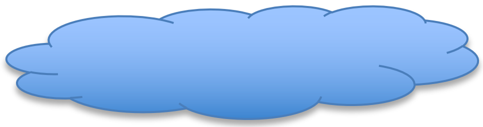


SW, CESM2-CAM6 (global-mean, January)

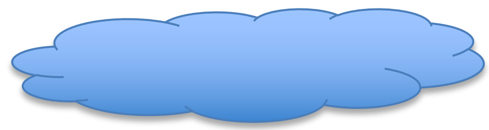


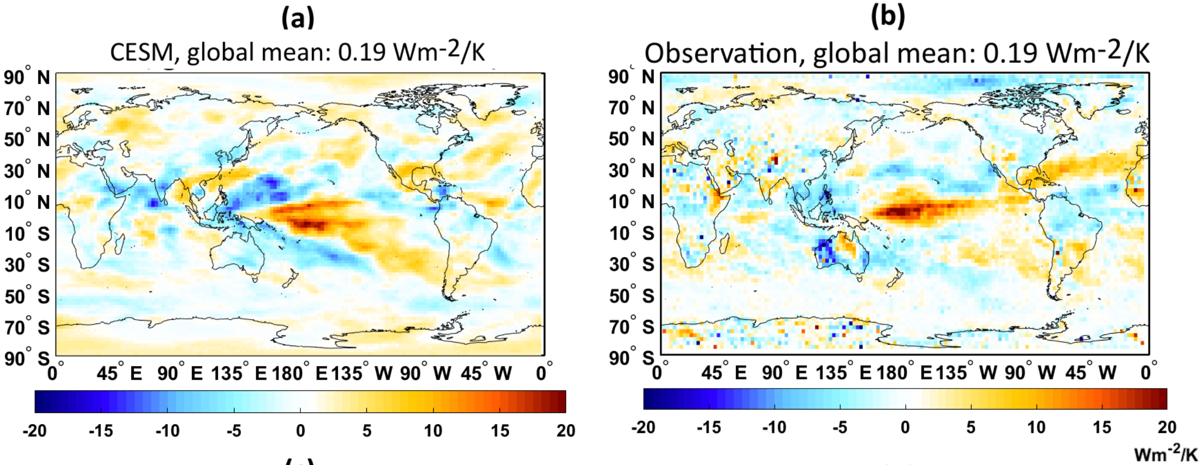
Why need it?

Affect both far-IR and window band

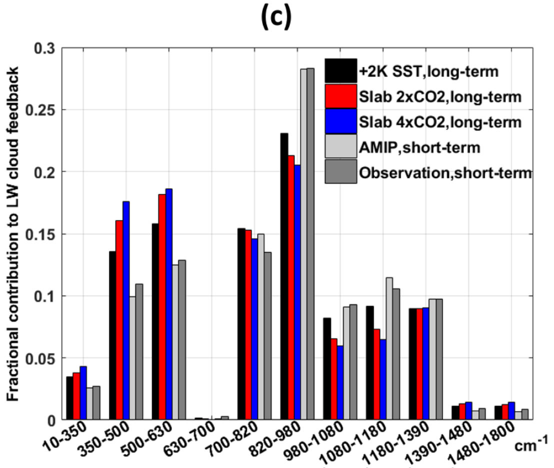


Affect only window band but only far-IR





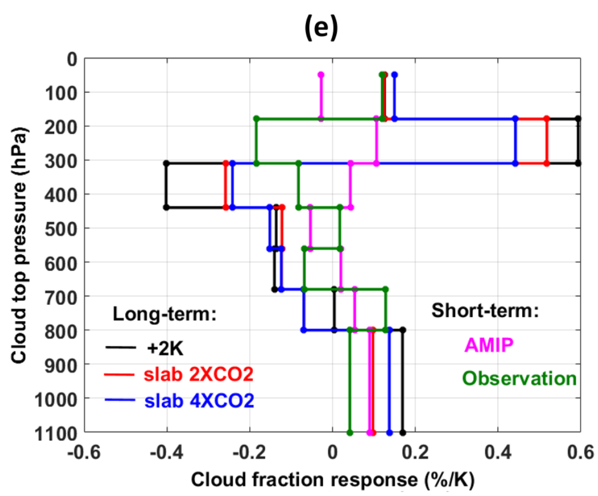
$2xCO_2$ CRF: 0.18 Wm^{-2}/K



(d)

	Total fractional contribution from 10-630 cm^{-1} (far-IR)	Total fractional contribution from 820-1180 cm^{-1} (window)
+2K SST	0.33	0.40
Slab $2xCO_2$	0.38	0.35
Slab $4xCO_2$	0.40	0.33
AMIP	0.25	0.49
Observation	0.26	0.48

CESM1-CAM4 experiment only



Long-term vs short term:
Different cloud amount change
Lead to
Different far-IR vs. window partitioning

(Huang et al., 2019)

Conclusions and Discussions

- To use one set of CRK to get all CRFs from all models might not be the best way to go
  - Cloud-radiation scheme is much more diversified among models than clear-sky schemes.
  - Further test out: try each CRK with their own $2xCO_2$ cloud changes
- If you are interested in the CESM CRK, you can get from
  - http://www.umich.edu/~xianglei/datasets.html
- Draft GFDL into this, and look for more modeling centers to participate
- http://www.umich.edu/~xianglei/cloud_kernel.html

An open project for model-based cloud radiative kernel development

by Xianglei Huang(Univ. of Michigan) and Qing Yue(JPL/Caltech)

Introduction:

This is a project to build cloud radaitive kernel for each particpating climate model using the method pioneered in Yue et al. (2016) and extended into the climate model applications by Huang et al. (2019). The method utilizes the output from each individual model without engaging any offline radiative transfer calculation. As such, the radaitive kernel is derived from the statistics of each model itself and avoids the issue that different models can have very different mean states and variability in terms of clouds.

If you are interested in participating in this project, below is a list of the variables needed for building the cloud radiative kernel. Once such set of data is provided, we will use the method described in Yue et al. (2016) to construct a set of cloud radiative kernel from the output.

Please email us if you are interested in particpation. We will provide ftp instruction for you to upload your data.

Experiment Set-up and List of varibles

Slab-ocean or fully-coupled simulation with constant forcing is preferred. If not practical, AMIP-type simulation with climatological SST is recommended.

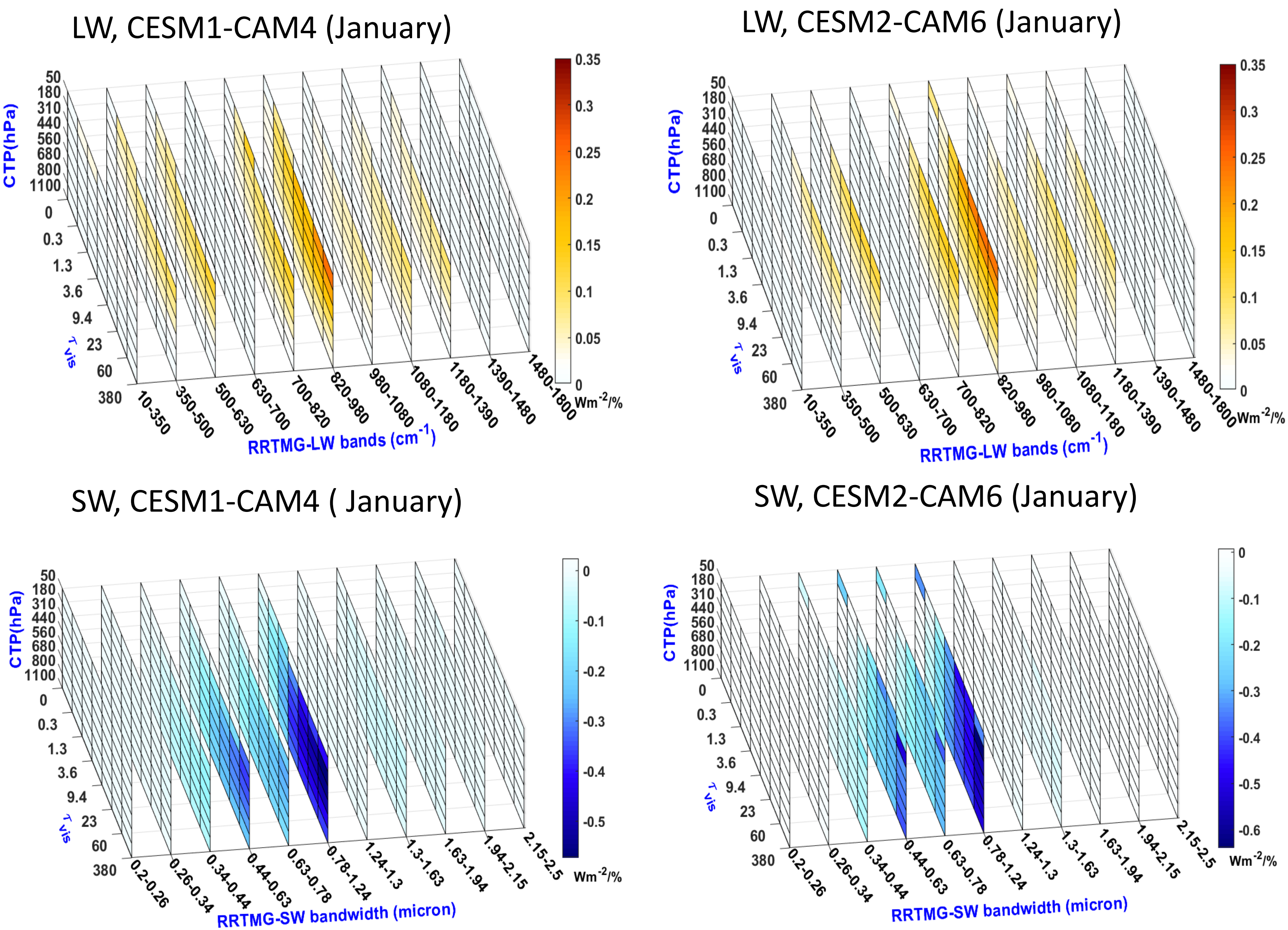
Please run the model for **10 years** (spin-up time not included), and archive **3-hourly** instantaneous fields for following variables:

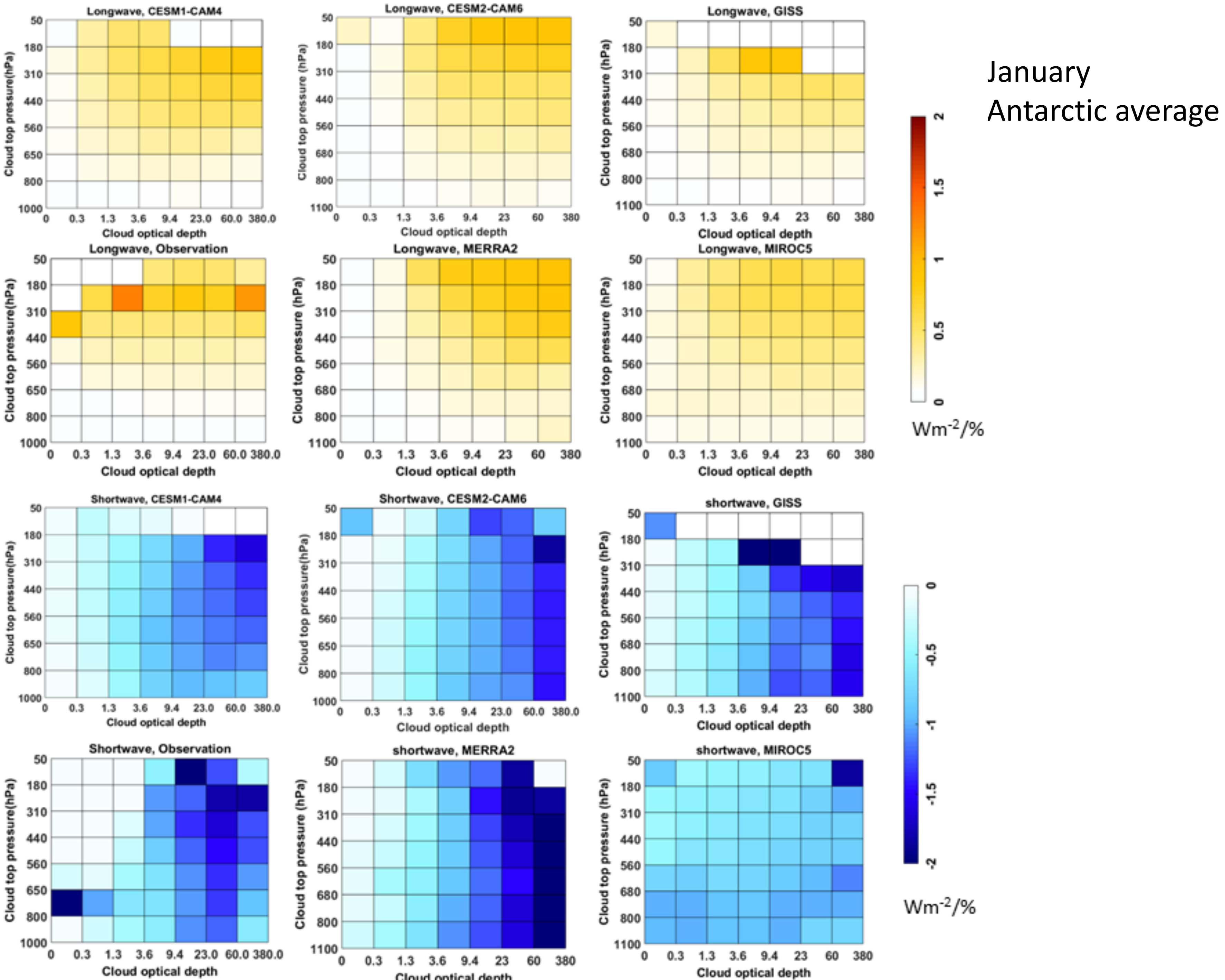
- 1. Surface temperature (2D)
- 2. Surface pressure (2D)
- 3. Atmospheric temperature profiles (3D)
- 4. Atmospheric specific humidity profiles (3D)
- 5. Cloud fraction (3D)
- 6. Liquid water content (3D)

References:

1. Huang, X.L., X. H. Chen, Q. Yue, 2019: Band-by-band contributions to the longwave cloud radiative feedbacks, Geophys. Res. Letts., 46, doi.org/10.1029/2019GL083466.
2. Yue, et al., 2016: Observation-based Longwave Cloud Radiative Kernels Derived from the A-Train, J. Climate, 29.
3. Zelinka, et al., 2012: Computing and partitioning cloud feedbacks using cloud property histograms. Part I: Cloud radiative kernels. J. Climate, 25, 3715–3735.

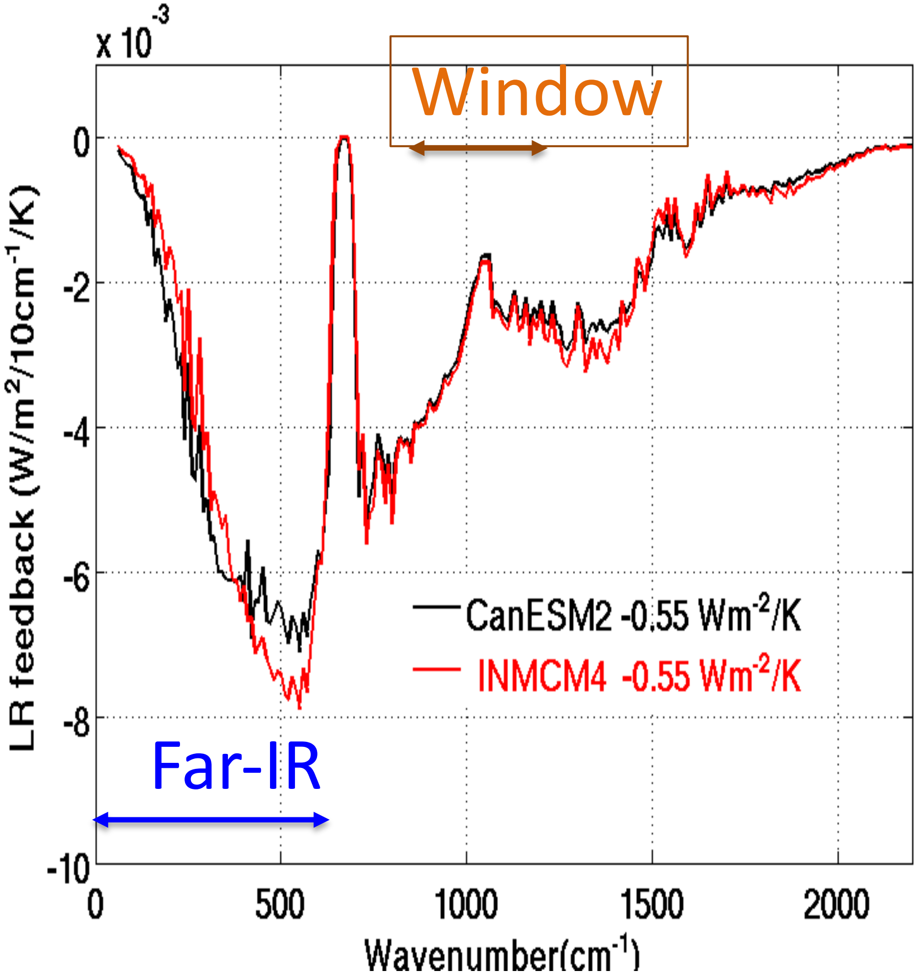
AMIP run, Antarctic





January
Antarctic average
Longwave, CESM1-CAM4
Longwave, CESM2-CAM6
Longwave, GISS
Longwave, Observation
Longwave, MERRA2
Longwave, MIROC5
Shortwave, CESM1-CAM4
Shortwave, CESM2-CAM6
shortwave, GISS
Shortwave, Observation
shortwave, MERRA2
shortwave, MIROC5
Cloud top pressure(hPa)
Cloud optical depth
Wm-2/%

Why do we care about spectral decomposition ?



Spectral decomposition of broadband lapse-rate feedback (Huang et al., 2014, GRL)

Far-IR: sensitive to upper & middle troposphere
Window: sensitive to PBL

Questions to answer (II):

- **How different the band-by-band decompositions of cloud feedbacks are**

  - ❑ **w.r.t. different warming scenarios?**
  - ❑ **between long-term and short-term (~10 years)?**
  - ❑ **between model and observation ?**

Using the NCAR CESM to test out

Methodology (model-based cloud radiative kernel)

- 3-hourly outputs (cloud fraction, clear-sky and all-sky TOA flux, etc.) from CESM simulations, 10 years
- Follow Yue et al. (2016) approach
  - Derive CTP, cloud optical depth from 3-hourly cloud profiles for each grid
  - Derive monthly-mean ISCCP-like histograms of cloud fraction (CF) and CRE
  - Compute cloud radiative kernel (CRK =CRE/CF) for each grid and each calendar month
- For both broadband and 16 RRTMG_LW bands

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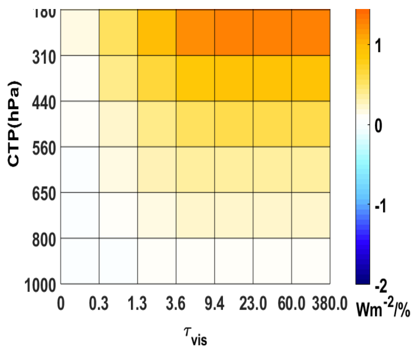
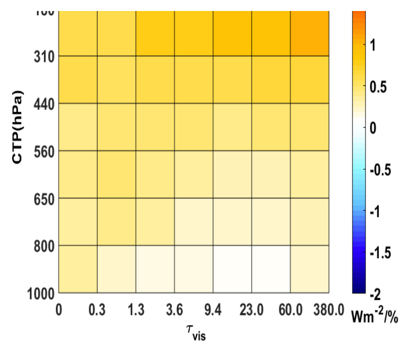
Derived LW cloud radiative kernels (globe, January)

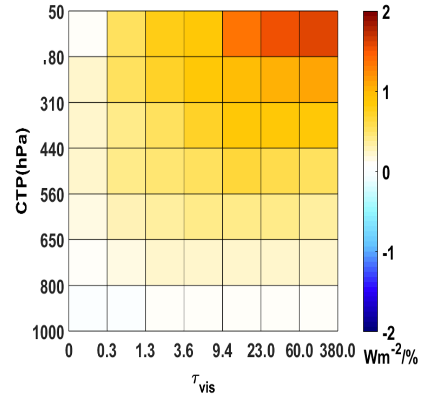
RT-based kernel (Zelinka et al., 2012)



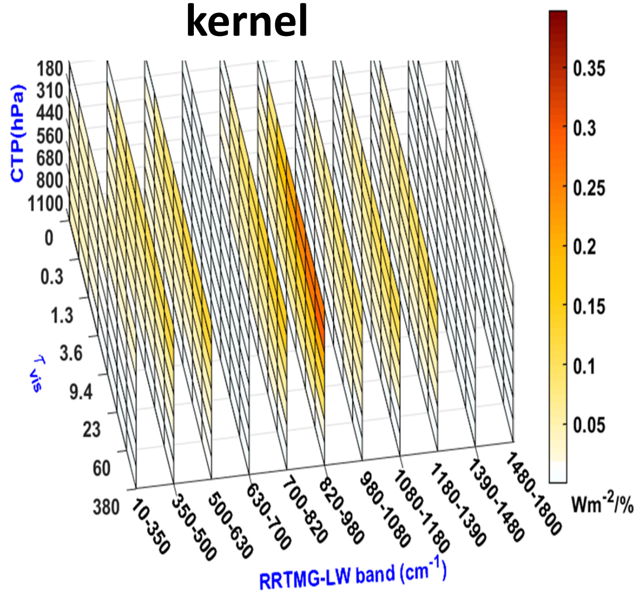
MODIS/AIRS-based kernel (Yue et al. 2016)



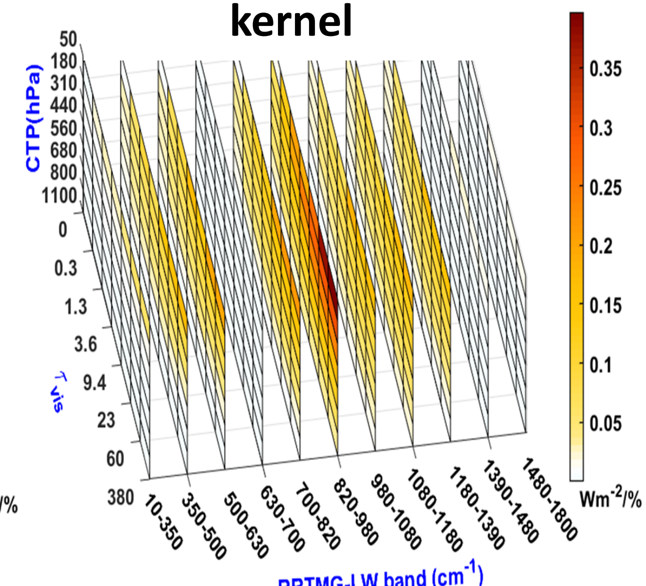
CESM-based kernel (This study)



kernel



kernel



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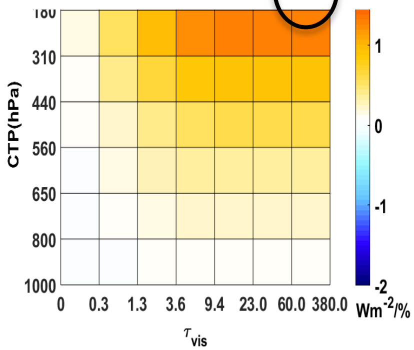

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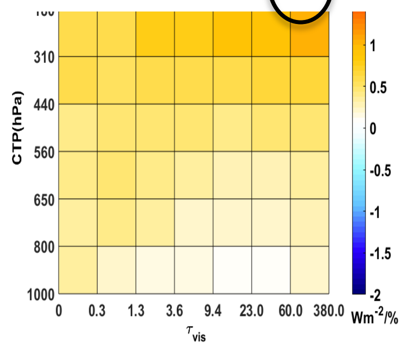

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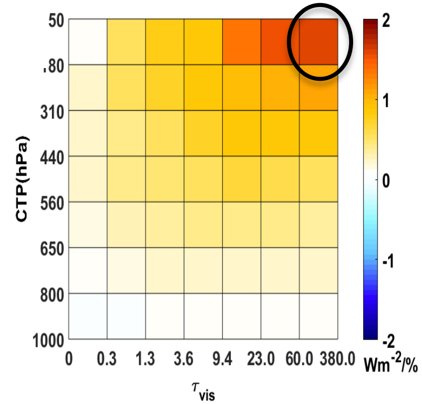

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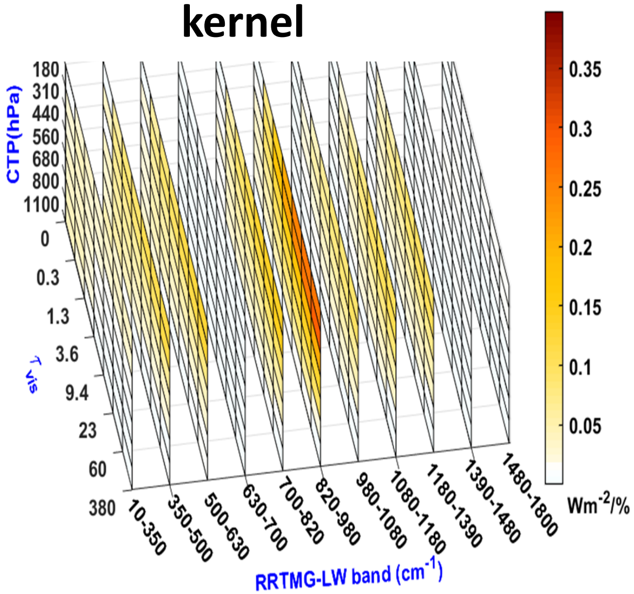
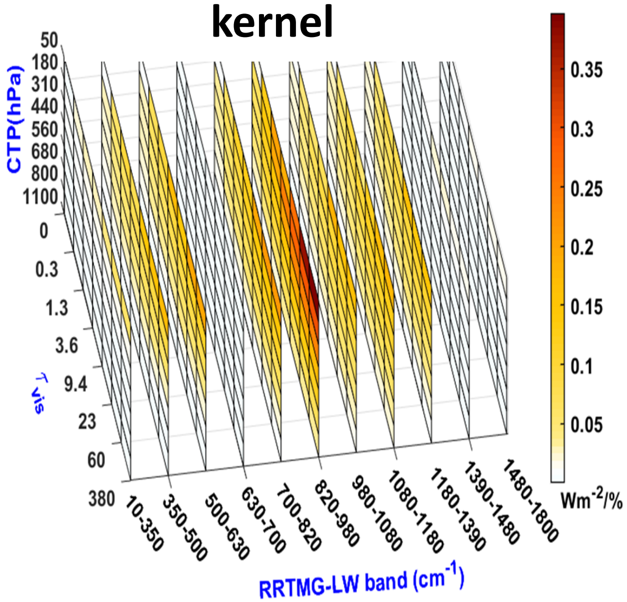


CESM-based kernel



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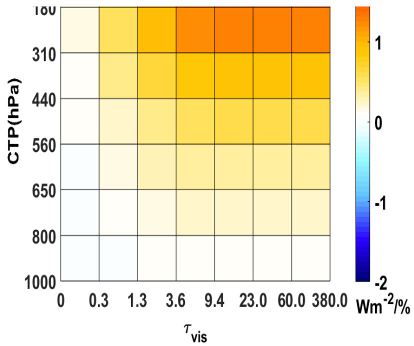

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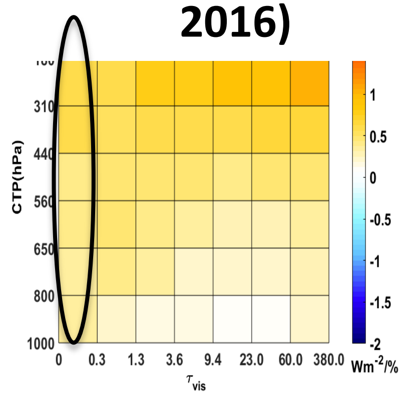

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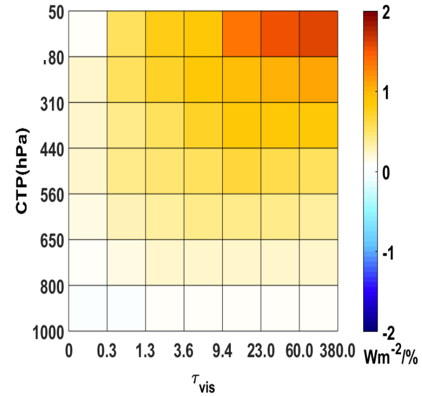

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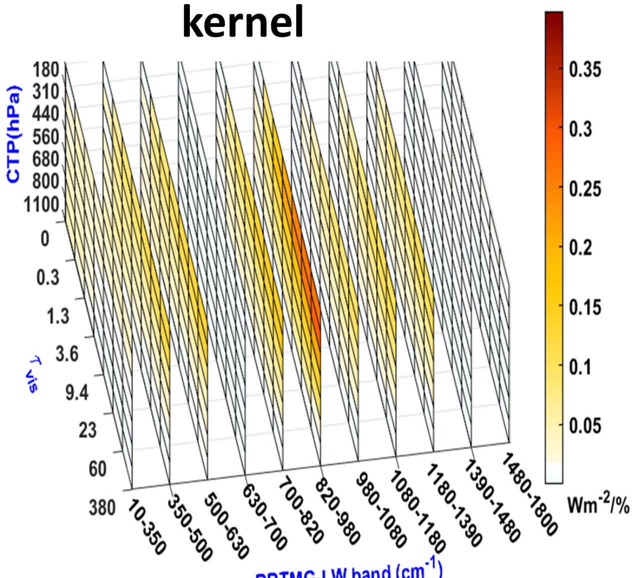

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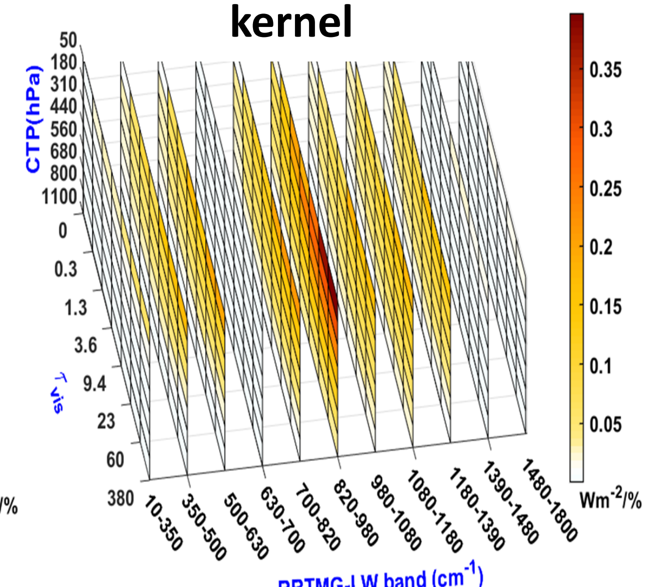

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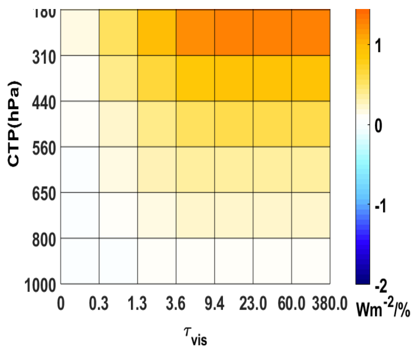

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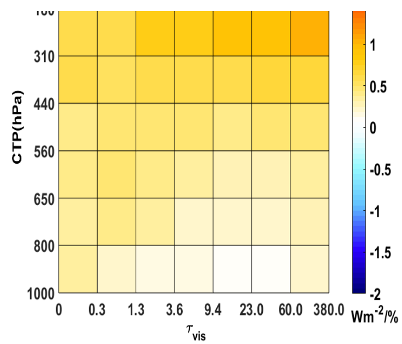

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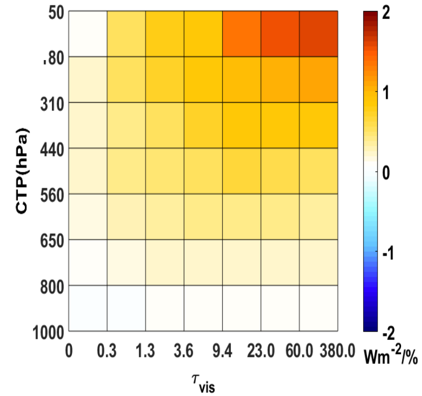

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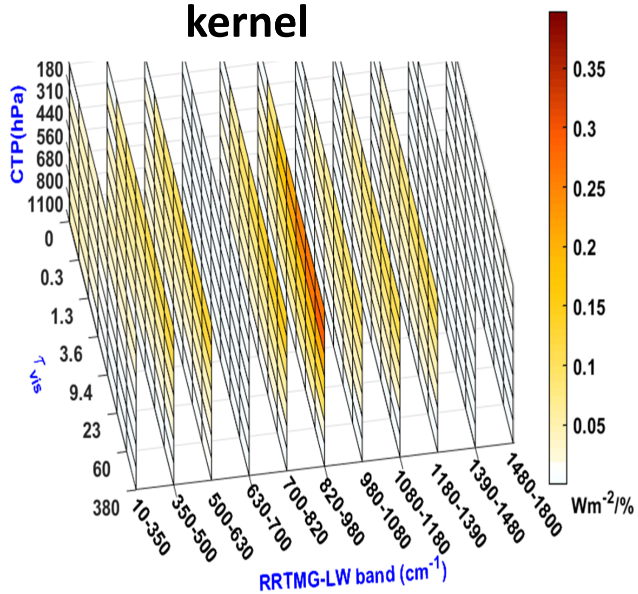

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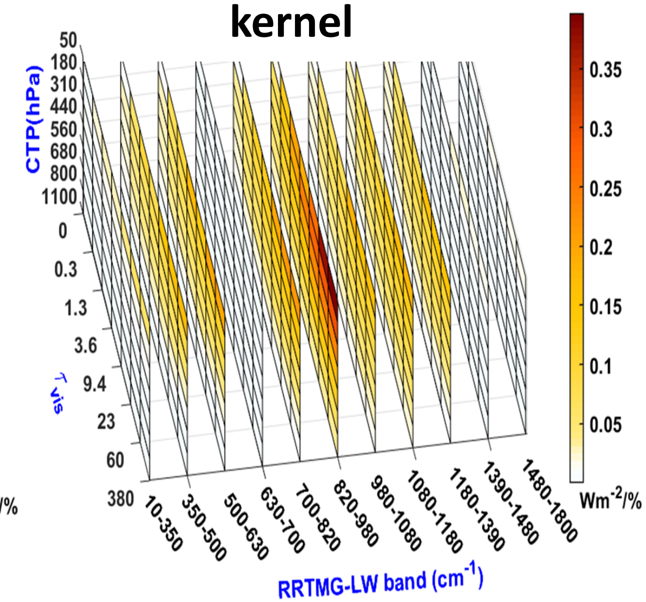

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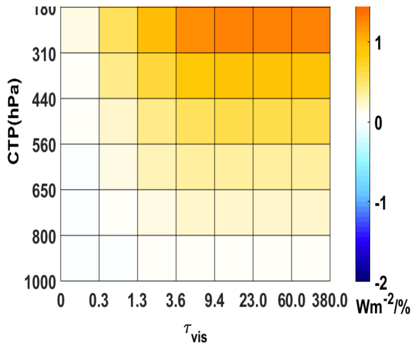

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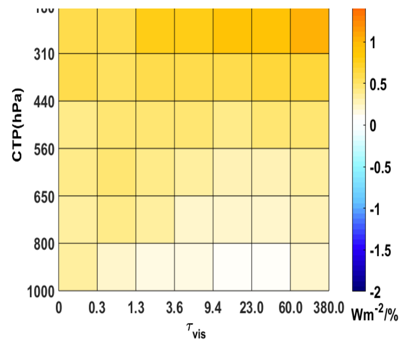

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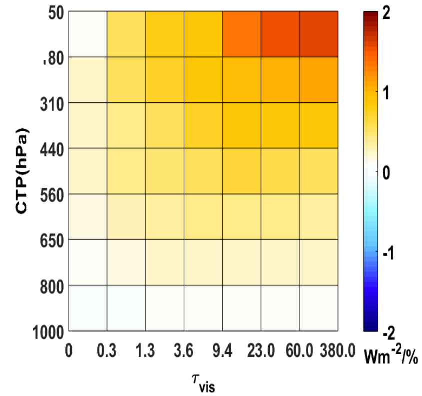

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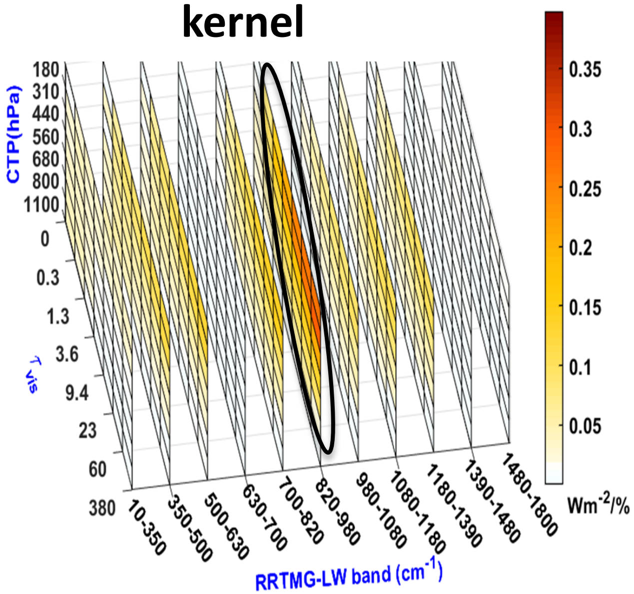

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